Influence of Experience and the Surgical Learning Curve on Long-term Patient Outcomes in Cardiac Surgery

Impact of Experience and the Surgical Learning Curve on Long-Term Patient Outcomes in Cardiac Surgery

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ABSTRACT

OBJECTIVE: We hypothesized that increased post-graduate surgical experience correlates with improved operative efficiency and long-term survival in standard cardiac surgery procedures.

METHODS: Utilizing a prospectively collected retrospective database, we identified patients who underwent isolated CABG (n=3726), AVR (n=1626), MV repair (n=731), MVR (n=324), and MVR+AVR (n=184) from 1/2002-6/2012. After adjusting for patient risk and surgeon variability, we evaluated the impact of surgeon experience on cardiopulmonary bypass and cross-clamp times, and long-term survival.

RESULTS: Mean surgeon experience after fellowship graduation was 16.0±11.7 years (1.0-35.2 years). After adjusting for patient risk and surgeon-level fixed effects, learning curve analyses demonstrated improvements in cardiopulmonary bypass and cross-clamp times with increased surgeon experience. There was marginal improvement in the predictability (R^2 value) of cardiopulmonary bypass and cross-clamp time for CABG with the addition of surgeon experience, however, all other procedures had marked increases in the R^2 following addition of surgeon experience. Cox proportional hazard models revealed that increased surgeon experience was associated with improved long-term survival in AVR (HR=0.85, P<0.0001), MV repair (0.73, p<0.0001), and MVR+AVR (0.95, p=0.006) but not in CABG (HR=0.80, p=0.15), and a trend towards significance in MVR (HR=0.87, p=0.09).

CONCLUSIONS: In cardiac surgery, not including CABG, surgeon experience is an important determinant of operative efficiency and of long-term survival.

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CENTRAL MESSAGE

Years in practice is a metric of surgeon experience that independently predicts operative efficiency and long-term survival in cardiac surgery valve procedures.

PERSPECTIVE STATEMENT

Whereas competence in cardiac surgery can be achieved in the current era of surgical training programs, excellence and mastery requires further postgraduate experience. Less common and more complex cardiac surgical procedures may require additional training and/or experience to achieve excellent outcomes.

INTRODUCTION

Adult cardiac surgery is a technically complex discipline that requires significant training to achieve operative proficiency. Mastery of operative procedures in this discipline requires experience beyond that which occurs in residency and fellowship training programs. Surgical learning curve analyses have found that surgical performance improves significantly over the course of an individual surgeon's career [1, 2]. In line with these observations, our group recently reported that attending cardiac surgeon experience (years since fellowship graduation) was significantly associated with a reduction in cardiopulmonary bypass (CPB) and cross-clamp times in coronary artery bypass grafting (CABG) procedures [2]. There is a large body of literature on the effects of individual surgeon volume on perioperative morbidity and mortality following surgical procedures. For the majority of cardiac operations, the balance of evidence suggests that higher individual surgeon volume is associated with improved postoperative morbidity and mortality [3-9], although there are some studies that fail to demonstrate this relationship[8, 10-12]. The effect of surgeon experience on learning curves of operative proficiency across a range of standard cardiac surgical procedures has not been formally tested. Further, the effect of surgeon experience on long-term survival across this range of cardiac surgical procedures has not yet been examined. We hypothesized that increased post-graduate surgical experience would correlate with improved operative efficiency (CPB and X-clamp times), and long-term survival in a variety of standard cardiac surgical procedures.

METHODS

From a prospectively collected, retrospective institutional database we identified all isolated CABG, aortic valve replacement (AVR), MV (mitral valve) repair, mitral valve replacement (MVR), and MVR+AVR (double valve) procedures performed at a single institution from 1/1/2002 to 6/30/2012. Preoperative, operative, and postoperative characteristics were captured in this prospectively collected database modeled after the Society of Thoracic Surgeons national database criteria [13]. Overall survival was collected using a combination of the Social Security Death Index and institutional follow-up data. Surgeon experience was defined as the number of years since cardiothoracic fellowship graduation of the date of the procedure. Our study was approved by the Brigham and Women's Hospital Institutional Review Board.

Statistics. All statistical analyses were performed using SAS software (SAS Institute Inc, Cary, NC). The primary dependent variables included CPB time, cross-clamp time, 30-day mortality, and overall survival. To create a patient-level summary measure of case severity and identify significant predictors of CPB time, cross-clamp time, and survival we used linear regression modeling. Covariates for predicting CPB time, cross-clamp time, and survival measures included patient age, sex, body mass index, height, weight, ejection fraction, unstable angina, (no myocardial infarction <7 days), myocardial infarction, cardiogenic shock, congestive heart failure/New York Heart Association functional class, cerebrovascular disease/cerebrovascular accident, diabetes, preoperative dialysis, preoperative creatinine, operative urgency status, preoperative arrhythmia, COPD (stage 3-4 chronic lung disease), current smoking status, reoperation, and previous cardiovascular intervention. Covariates were selected on the basis of having a previously documented association with the length of CPB time, cross-clamp time, or mortality [14] and a low rate of missing data. Model selection to create a robust multivariate patient risk adjustment model independently for CPB, cross-clamp time, and overall survival was performed using the approach described by Collett [15]. Each procedure was evaluated as a separate model. Briefly, following univariate analysis for each preoperative and operative predictor, those with a parameter P value <0.15 were selected for initial entry into the multivariate model. After initial fitting, nonsignificant variables were eliminated using backward selection (P < 0.1). Nonsignificant univariate predictors were subsequently tested using forward selection (P = 0.1) and all possible 2-way interactions were tested using forward selection (P = 0.1 for entering). Finally, all nonsignificant main effects (unless a component of an interaction term) and non-significant interactions were removed.

Following adjustment of patient risk characteristics, and fixed surgeon effects using generalized estimating equations fixed effects modeling (GLM procedures) by surgeon level, attending surgeon experience was entered into each model (CPB time, cross-clamp time, 30-day mortality and overall survival) as a continuous variable. The expected performance curve of surgical teams over time was generated based on a multivariate generalized estimating equation regression model. CPB time, cross-clamp time, and overall survival were the outcomes of interest, whereas attending experience was the predictor, and patient case mix was considered as covariate in the final model. Because the CPB and cross-clamp time curves may not necessarily be a linear function of surgeon experience, we also considered models with quadratic or logarithmic terms in surgeon experience and chose the model with the best fit.

RESULTS

Our patient cohort included 6591 patients comprised of 3726 CABG (56.5%), 1626 AVR (24.7%), 731 MV repair (11.1%), 324 MVR (4.9%), and 184 MVR+AVR procedures (2.8%). Mean patient age was 66 ±12 years and 67.8% of patients were male. Patient risk factors and characteristics for each procedure are shown in Table 1. There were 10 surgeons with varying years of post-graduate experience. The mean surgeon years of experience was 16.0 ±11.7 years, with a range of 1.04 to 35.18 years. The total number of cases performed by an individual surgeon over the period of study ranged from 75 to 1660, and the case mix stratified by years of surgeon experience is shown in Table 2.

To test whether ~~operative efficiency~~ CPB and cross-clamp times are influenced by surgeon experience in AVR, MV repair, MVR, and MVR+AVR procedures in a similar way that we have shown to be true for CABG procedures [2], we constructed patient risk-adjusted and surgeon-level fixed effects adjusted CPB time and cross-clamp time experience curves for each of these procedures (Figures 1A and 2A). Scatter plot readouts of the linear regression analyses from which these curves are derived are shown in Supplemental Figures 3 and 4. For all procedures, the mean CPB times were 112.5 ±48.7 minutes (range 16-596 minutes) and the mean cross-clamp times were 81.7 ±33.9 minutes (range 8-386 minutes). The procedures had markedly different efficiency learning curves for both CPB time and cross-clamp time. For CPB time, the learning curve for each procedure was characterized by a statistically significant improvement with increasing post-graduate surgical experience (-0.33 β coefficient for CABG, -0.89 for AVR, -1.30 for MV repair, -1.51 for MVR, -2.22 for MVR+AVR; p<0.001 for all procedures). For cross-clamp time, the learning curve for each procedure was characterized by a statistically significant improvement with increasing post-graduate surgical experience (-0.44 β coefficient for CABG, -0.83 for AVR, -1.11 for MV repair, -0.87 for MVR, -2.01 for MVR+AVR; p<0.001 for all procedures). To determine the predictive effect of surgical experience, R^2 values were measured after adjusting for patient risk and surgeon-level fixed effects, and before the addition of surgical experience as well as after the addition of surgeon experience (Figures 1B and 2B). There was marginal improvement in the predictability of CPB and cross-clamp time for CABG with the addition of surgical experience; however, the addition of surgeon experienced markedly increased the adjusted R^2 value (explanatory variability in predicting CPB and cross-clamp times) in AVR, MV repair, MVR, and MVR+AVR.

The unadjusted overall 30-day mortality was 1.3% for CABG, 2.4% for AVR, 0.7% for MV repair, 4.9% for MVR 4.9% and 4.3 % for MVR+AVR. The mean follow-up time was 5±3 years. To determine whether surgeon experience influenced 30-day mortality in these procedures, Cox proportional hazard models were constructed for each procedure (Table 3). Controlling for each patient risk and surgeon-level fixed effects, these analyses revealed an independent predictive effect of surgeon experience on 30-day mortality in the three least common procedures performed during this time period, MV repair (OR 0.63, p<0.0001), MVR (OR 0.73, p=0.001), and MVR+AVR (OR 0.86, p=0.0004), and did not influence 30-day mortality in CABG or AVR procedures. To determine whether surgeon experience influenced long-term survival in each of the 5 procedures, additional Cox proportional hazard models were constructed for each procedure with overall survival as the outcome variable (Table 4). Controlling for patient risk and surgeon-level fixed effects, these analyses revealed an independent predictive effect of surgeon experience on long-term survival in AVR (HR 0.85, p<0.0001), MV repair (HR 0.73, p<0.0001), and MVR+AVR (HR 0.95, p=0.006). There was a trend towards a significant effect of the influence of surgeon experience on long-term survival following MVR (p=0.09) and no significant effect of surgeon experience on long-term survival in CABG (p=0.15).

In addition to the surgeon experience metric of post-graduate years of experience, we examined cumulative case volume as a predictor of long-term survival for each separate procedure. These results are shown in Supplementary Table 1 and reveal that cumulative case volume was a significant predictor of long-term survival in AVR and MV repair procedures.

DISCUSSION

The principal finding in this paper is that post-graduate surgical experience drives not only operative efficiency, but also long-term survival in cardiac surgery valve procedures. These data have important implications for models of postgraduate learning that include apprenticeship and simulation training.

It is reasonable to propose that increasing surgeon experience correlates positively with improved surgical technique, and it is our opinion that surgical technique directly influences long-term survival outcomes in cardiac surgery. Technical proficiency likely relates to durability of valve repair and graft patency, and these factors likely translate into advantages, or disadvantages, in long-term survival.

The metric of surgeon experience that we examined in this study was time since postgraduate training. Compared to more widely studied learning curve metrics such as case volume, we believe that years since postgraduate training may capture intangible factors related to surgical acumen and judgment. Whereas time since postgraduate training has not been thoroughly studied as a predictor of short-term outcomes in cardiac surgery, it has been previously shown in a single institution study that lower academic seniority was associated with longer CABG operative times, perfusion times, and cross-clamp times, but not with postoperative morbidity or mortality [16]. The groups that were compared in this study, however, were faculty and first and second year cardiothoracic fellows; experience as a faculty member was not examined.

A large body of literature has established a positive relationship between hospital volume and short-term operative morbidity and mortality across a variety of medical and surgical procedures. Importantly, recent evidence suggests that the associations between hospital volume and surgical mortality are mediated by surgeon volume [3], and surgeon volume has, in fact, been found to have a greater influence on patient outcomes than hospital volume [17]. In cardiac surgery, specifically, increasing surgeon volume has been associated with improved postoperative morbidity and mortality in on-pump CABG [3, 6-8], off-pump CABG [9], AVR [3, 4], and minimally invasive mitral valve surgery [5].

To the best of our knowledge, this is the first report to rigorously examine years since postgraduate training as a predictor of long-term survival in cardiac surgery procedures. Our hypothesis was that this metric of surgeon experience would correlate with improved overall survival. In AVR, MV repair, and MVR+AVR, we found years since postgraduate training to be an independent predictor of long-term survival, and we found a similar trend for MVR procedures. Separately, we examined an additional metric of surgeon experience, cumulative case volume, and found that case volume was predictive of long-term survival in AVR and MV repair operations, but not in in MVR, MVR+AVR operations, or CABG operations. Taken together, these data suggest that years since postgraduate training and cumulative case volume are different surgeon experience metrics with different predictive abilities in cardiac surgery procedures. In our dataset, years since postgraduate experience correlated with long-term survival in a greater range of valve procedures than did cumulative case volume.

It is noteworthy that surgeon experience was not associated with statistically significant improvements in long-term (or 30-day) mortality following CABG procedures. Similarly, the magnitude of improvement in CPB and cross-clamp time, was only clinically meaningful for AVR, MV repair, MVR, and MVR+AVR procedures, and not for CABG. In our study, CABG was by far the most common of all performed procedures (57%). One interpretation of these data is surgical maturity is attained for this procedure during cardiothoracic fellowship and this decreases the surgical learning curve during a surgeons faculty career. The influence of training on this procedure is highlighted in a recent publication by our group that demonstrated that the cumulative experience of attending cardiac surgeons and cardiothoracic fellows had a dramatic effect on CPB and cross-clamp times, and that the influence of attending-fellow pair experience far exceeded the influence of individual surgeon experience [2]. Another potential explanation for this finding is that CABG is a mature "technology" whose basic underlying principles are familiar to graduates of surgical training programs and may, therefore, require less of a learning curve today than in previous decades.

An additional element to take into consideration is that, although our study is not focused on gaps in recent surgical training, surgical training has certainly changed over the course of the last 35 years, which was the span of surgical experience in our dataset. If it is assumed that there is no meaningful difference in individual surgical learning curves among different eras of surgical training, this implies that either surgical training in valve procedures has not been as effective as it was for coronary revascularization procedures, or that the complexity and rapid evolution in valvular procedures may be responsible for the dichotomy between the CABG and valve data. Our study is not aimed, however, at examining the effects of surgical training on surgical outcomes, but is focused on surgeon experience following cardiothoracic surgery residency. It is our opinion that competence in cardiac surgery can be achieved in the current era of surgical training programs, however excellence and mastery requires further postgraduate experience.

The strengths of our study include a robust prospectively collected database from which it is derived and complete long-term follow-up on a large cohort of patients operated on by 10 surgeons with a wide variance of years of experience. Our study is limited by the selection and information biases inherent to retrospective analyses. Additionally, our study was performed at a single academic institution where different postgraduate year levels of residents are involved in these procedures, and this may account for some degree of confounding in our study that was not measured. Accordingly, our data may not be representative of the majority of cardiac surgery that is routinely performed in the United States. Several other elements of our dataset deserve mention as potential limitations. First, there was some variability in the total number of cases and number of specific cases performed by surgeons with similar levels of experience, which may have influenced our results. Additionally, the majority of AVRs (62%) and MV repairs (58%) were performed via hemisternotomy. At our institution, these procedures are typically performed by more experienced valve surgeons, and we believe that the performance of such procedures likely reflects and evolution of a surgeon as he or she progresses along his or her learning curve.

In conclusion, we have shown that increasing years of surgeon experience is associated with improved operative efficiency and long-term mortality in valvular cardiac surgery. It is our opinion that cardiothoracic training programs appear to provide adequate training in CABG procedures. Less-common and more-complex procedures, however, may require further training to achieve excellent outcomes. A similar phenomenon may occur with CABG as it is supplanted by improved interventional techniques and used on increasingly complex patients. Also implied by our data is that learning curves are more likely to exist when new technologies such as robotics or new procedures such as transaortic/transapical aortic valves [18, 19], minimally invasive CABG [20, 21] or minimally invasive mitral valve surgery [5] are introduced into a surgeon's repertoire.

Table 1. Patient Characteristics

Characteristic	CABG	AVR	MV Repair	MVR	MVR + AVR
Age (years)	66 ± 11	69 ± 14	58 ± 13	63 ± 15	64 ± 14
Male	76%	56%	64%	40%	52%
Body Mass Index	29 ± 5	28 ± 6	25 ± 4	27 ± 6	27 ± 6
Height (cm)	172 ± 10	169 ± 11	173 ± 10	167 ± 10	169 ± 11
Weight (kg)	86 ± 18	81 ± 19	76 ± 15	76 ± 20	76 ± 19
Ejection Fraction	58 ± 10	56 ± 11	61 ± 8	56 ± 12	57 ± 11
Angina	72%	19%	6%	10%	12%
Myocardial Infarction	45%	10%	3%	11%	4%
Family History of CAD	30%	20%	18%	19%	19%
Congestive Heart Failure	25%	36%	24%	59%	59%
Cardiogenic Shock	2%	1%	0%	3%	0%
NYHA Class					
1	19%	15%	33%	10%	8%
2	44%	45%	45%	32%	35%
3	29%	36%	21%	50%	57%
4	8%	4%	1%	8%	1%
Arrhythmia	5%	9%	8%	22%	21%
Cardiovascular Accident	5%	4%	1%	10%	9%
Cerebrovascular Disease	12%	10%	4%	15%	16%
Diabetes	38%	20%	4%	18%	21%
COPD	10%	16%	10%	23%	26%
Current or Previous Smoker	59%	45%	33%	45%	49%
Operative Urgency					
Elective	44%	83%	94%	68%	67%
Urgent	52%	16%	6%	27%	30%
Emergent	4%	1%	0%	5%	3%
Reoperation	14%	19%	4%	43%	47%
Creatinine	1.1 ± 0.8	10.8 ± 0.6	1.0 ± 0.4	1.2 ± 0.9	1.4 ±` 1.4

Standard deviation is shown following mean values for continuous variables.

Table 2. Post-graduate surgeon experience and number of cases performed.

Years Experience	Total Cases	CABG	AVR	MV Repair	MVR	MVR+AVR
1	301	233	47	9	8	4
2	304	258	33	8	5	0
3	297	226	42	13	8	8
4	352	253	73	10	10	6
5	429	307	84	20	10	8
6	343	234	79	14	8	8
7	127	51	47	10	15	4
10	103	72	27	1	3	0
11	139	119	11	3	2	4
12	206	175	20	4	5	2
13	209	154	36	5	12	2
14	353	271	52	11	11	8
15	434	331	60	15	12	16
16	318	205	64	25	18	6
17	278	192	49	14	13	10
18	234	163	45	16	10	0
19	200	130	47	14	7	2
20	147	86	34	12	11	4
21	55	18	21	7	3	6
22	51	17	17	9	4	4
23	64	22	25	11	4	2
24	40	18	14	7	1	0
25	45	16	10	7	6	6
26	47	3	25	12	3	4
27	37	6	17	6	4	4
28	32	8	15	5	2	2
29	1	0	1	0	0	0
30	79	22	22	24	11	0
31	149	33	55	48	11	2
32	165	29	68	59	5	4
33	201	26	100	55	16	4
34	194	14	78	84	16	2
35	657	34	308	193	70	52

Table 3. Independent effect of surgeon experience on 30-day mortality.

Operation	Odds Ratio	Confidence Interval	p value
CABG[1]	1.022	0.951-1.097	0.5525
AVR[2]	0.995	0.918-1.079	0.9011
MV Repair[3]	0.633	0.534-0.750	<0.0001
MVR[4]	0.732	0.607-0.883	0.001
AVR + MVR[5]	0.863	0.795-0.936	0.0004

Surgeon experience was corrected for the following additional variables predictive of 30-day survival in multivariate analyses in each model.

[1]CABG: cerebrovascular accident, reoperation

[2]AVR: age, angina, creatinine, ejection fraction, current smoker

[3]MV Repair: age, reoperation, urgent/emergent operation

[4]MVR: ejection fraction, reoperation, emergent operation

[5]MVR+AVR: congestive heart failure, creatinine

Table 4. Independent effect of surgeon experience on long-term survival.

Operation	Hazard Ratio	Confidence Interval	p value
CABG[1]	0.802	0.593-1.083	0.15
AVR[2]	0.852	0.801-0.906	<0.0001
MV Repair[3]	0.732	0.627-0.854	<0.0001
MVR[4]	0.874	0.748-1.021	0.09
AVR + MVR[5]	0.947	0.910-0.985	0.006

Surgeon experience was corrected for the following additional variables predictive of long-term survival in multivariate analyses in each model.

[1]CABG: congestive heart failure, cerebrovascular accident, cardiogenic shock, height (cm), myocardial infarction, previous cardiac surgical procedures

[2]AVR: age, angina, last creatinine, ejection fraction (low), current smoking

[3]MV Repair: age, previous cardiovascular intervention, urgent/emergent operation

[4]MVR: cardiogenic shock, current smoking

[5]MVR+AVR: congestive heart failure, last creatinine

Supplemental Table 1. Effect of cumulative surgeon volume on long-term survival.

Operation	**Hazard Ratio**	**Confidence Interval**	**p value**
CABG	0.997	0.961, 1.034	0.8753
AVR	0.944	0.918, 0.970	<0.0001
MV Repair	0.911	0.840, 0.989	0.0257
MVR	0.968	0.919, 1.019	0.2107
AVR + MVR	0.969	0.913, 1.029	0.3006

FIGURE LEGENDS

Figure 1. (A) Risk-adjusted cardiopulmonary bypass (CPB) time (minutes) are shown with respect to years of surgical experience for each procedure. All experience curves have $p<0.001$. (B) Best-fit cardiopulmonary bypass models are shown with R-squared values adjusted for patient risk and surgeon-level fixed effects (blue), and additionally adjusted for surgeon experience (red).

Figure 2. Risk-adjusted cross clamp time (minutes) are shown with respect to years of surgical experience for each procedure. All experience curves have $p<0.001$. (B) Best-fit cross-clamp models are shown with R-squared values adjusted for patient risk and surgeon-level fixed effects (blue), and additionally adjusted for surgeon experience (red).

Supplemental Figure 1. Scatter plots displaying results of linear regression analysis of cardiopulmonary bypass times for (A) CABG, (B) AVR, (C) MV repair, (D) MV replacement, and (E) MVR+AVR.

Supplemental Figure 2. Scatter plots displaying results of linear regression analysis of cross-clamp times for (A) CABG, (B) AVR, (C) MV repair, (D) MV replacement, and (E) MVR+AVR.

CENTRAL FIGURE

Figure 1a is designated as the central figure.

Figure legend for Central Figure. Risk-adjusted cardiopulmonary bypass (CPB) time decreases with increasing surgical experience.

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